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Priming sentence comprehension in aphasia: Effects of lexically independent and specific structural priming

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Abstract

Purpose. Impaired message-structure mapping results in deficits in both sentence production and comprehension in aphasia. Structural priming has been shown to facilitate syntactic production for persons with aphasia (PWA). However, it remains unknown if structural priming is also effective in sentence comprehension. We examined if PWA show preserved and lasting structural priming effects during interpretation of syntactically ambiguous sentences and if the priming effects occur independently of or in conjunction with lexical (verb) information.

Methods. Eighteen PWA and 20 healthy older adults (HOA) completed a written sentence-picture matching task involving the interpretation of prepositional phrases (PP; *the chef is poking the solider* *with an umbrella*) that were ambiguous between high (verb modifier) and low attachment (object noun modifier). Only one interpretation was possible for prime sentences, while both interpretations were possible for target sentences. In Experiment 1, the target was presented immediately after the prime (0-lag). In Experiment 2, two filler items intervened between the prime and the target (2-lag). Within each experiment, the verb was repeated for half of the prime-target pairs, while different verbs were used for the other half. Participants' off-line picture matching choices and response times were measured.

Results. After reading a prime sentence with a particular interpretation, HOA and PWA tended to interpret an ambiguous PP in a target sentence in the same way and with faster response times. Importantly, both groups continued to show this priming effect over a lag (Experiment 2), although the effect was not as reliable in response times. However, neither group showed lexical (verb-specific) boost on priming, deviating from robust lexical boost seen in the young adults of prior studies.

Conclusions. PWA demonstrate abstract (lexically-independent) structural priming in the absence of a lexically-specific boost. Abstract priming is preserved in aphasia, effectively facilitating not only immediate but also longer-lasting structure-message mapping during sentence comprehension.

Introduction

Impaired ability to use syntax is at the heart of difficulty producing and comprehending sentences in persons with aphasia (PWA) (Schwartz, Saffran, Fink, Myers, & Martin, 1994; Rochon, Laird, Bose, & Scofield, 2005; Thompson, Faroqi-Shah, & Lee, 2015). Although this deficit is more often associated with non-fluent aphasia, many individuals with fluent aphasia also demonstrate syntactic impairments (Caplan, Waters, DeDe, Michaud, & Reddy, 2007; McAllister, Bachrach, Waters, Michaud, & Caplan, 2009). PWA show difficulty producing sentences with non-canonical word order (e.g., passives) or complex verb argument structure (Caplan & Hanna, 1998; Bastiaanse & van Zonneveld, 2005; Lee, M. & Thompson, 2004). Similarly, in the domain of sentence comprehension, PWA show difficulty with non-canonical sentences (Caplan et al., 2007; Caramazza & Zurif, 1976; Thompson & Choy, 2009) or syntactically ambiguous sentences (DeDe, 2010). There is some evidence that PWA are impaired in predicting upcoming arguments based on verb meaning (Mack, Ji, & Thompson, 2013) and/or show a delay in accessing lexical information during sentence comprehension (Ferrell, Love, Walenski, & Shaprio, 2012; Love et al., 2008; Swaab et al., 1998). Other studies find that the ability to predict abstract syntactic structures may remain intact in PWA, at least when supported by strong and unambiguous morphosyntactic or lexical cues (Hanne, Buchert, De Bleser, & Vashishth, 2015; Thompson & Choy, 2010; Warren, Dickey, & Lei, 2016).

These impairments are often viewed as reflecting a ‘processing’ disorder in aphasia characterized by inefficient activation and computation of linguistic information rather than a loss of linguistic representations as such (e.g., Linebarger, Schwartz, Romania, Kohn, & Stephens, 2000; Haarmann & Kolk, 1991). Therefore, one crucial question has been to identify cognitive mechanisms or strategies that facilitate efficient and accurate message-structure mapping in PWA in both experimental (Lee, Yoshida, & Thompson, 2015; Thompson et al., 2015) and intervention studies (Rochon et al., 2005; Thompson, Shapiro, Kiran, & Sobecks, 2003). Lee and colleagues, examining real-time sentence planning processes, have shown that early access to syntactic configuration of verb arguments is crucial for accurate and fluent sentence production in those with agrammatic aphasia (Lee et al., 2015; Lee & Thompson, 2011a; 2011b). Moreover, there is increasing evidence suggesting that structural priming - an individual's inadvertent tendency to echo a previously encountered syntactic structure - can overcome computational overload during activation and selection of syntactic structures, demonstrating not only immediate but also longer-lasting facilitation of sentence production (Cho-Reyes, Mack, & Thompson, 2016; Hartsuiker & Kolk, 1998; Lee & Man, 2017; Saffran & Martin, 1997; see also Lee, Man, Ferreira, & Gruberg, under review). However, little is known if structural facilitation is also effective in sentence comprehension for PWA. The present study aims to examine the effect of structural priming on interpretation of syntactically ambiguous sentences in PWA.

Structural priming is pervasive in normal language processing: Language users' preferences of syntactic structures are influenced by syntactic structures that they have previously encountered (Pickering & Ferreira, 2008). For example, a speaker who heard a passive sentence (e.g., *the boy was bit by the dog*) is more likely to produce a passive rather than an active sentence (Bock, 1986; Bock, Dell, Chang, & Onishi, 2007). Similarly, using both off-line and on-line measures, studies of sentence comprehension have shown that structural priming effectively guides participants' interpretation of sentences that are temporarily ambiguous or facilitates prediction of upcoming arguments during sentence parsing (Arai, van Gompel, & Scheepers, 2007; Branigan, Pickering, & McLean, 2005; Ledoux, Traxler, & Swaab, 2007; Traxler & Tooley, 2008; Pickering, McLean, & Branigan, 2013; Thothathiri & Snedeker, 2008a; Traxler, 2008).

Two mechanisms are required to explain structural priming: long-term priming that is independent of lexical material (*abstract structural priming*) and lexically dependent enhancement in priming (*lexical boost*) that is generally short-lived. Priming occurs even though a prime sentence does not share any lexical-semantic materials with a target sentence, indicating the presence of priming at the level of abstract syntactic structure (Bock, 1989; Bock & Loebell, 1990). This priming effect remains overwhelmingly consistent over intervening fillers and multiple sessions, suggesting that it creates lasting modulations in the syntactic system (Cleland & Pickering, 2006; Bock & Griffin, 2000; Bock et al., 2007; Boyland & Anderson, 1998). However, when the same lexical items (e.g., verb) are repeated between prime and target, the priming effect becomes significantly enlarged, indicating that there is a separate mechanism of priming that is lexically-driven in nature (Hartsuiker et al., 2008; Pickering & Branigan, 1998; Scheepers, Raffray, & Myachykov, 2017). Crucially, the lexical boost effect is generally ephemeral, dissipating by the presence of only one intervening utterance (Branigan & McLean; 2016; Hartsuiker et al., 2008).

It is clear that both mechanisms of priming are also operative in normal sentence comprehension, although there is less empirical evidence available for the different time courses of lexically-independent vs. specific priming compared to the production literature. A group of studies reported that significant priming only occurs when the verb was repeated between prime and target, claiming that structural priming in comprehension is fully lexically-driven (Arai et al., 2007; Branigan et al., 2005; Ledoux et al., 2007; Traxler & Tooley, 2008). Others, however, have demonstrated significant priming without lexical overlap in both young adults (Thothathiri & Snedeker, 2008a; Tooley & Bock, 2014) and children (Thothathiri & Snedeker, 2008b). Most relevant to the current research, Pickering et al. (2013) showed that both abstract priming and lexical boost persist in comprehension. They examined the effects of same vs. different verb primes on comprehension of sentences with an ambiguous prepositional phrase (PP) such as *the artist is poking the clown* *<u>with the gun</u>* at both immediate (0-lag) and longer-term (1-lag and 2-lag) priming conditions. The PP can be interpreted to modify the verb (*poke*; high attachment) or the object noun (*the clown*; low attachment). Their young adults read a sentence and selected a picture that matched the sentence. For prime sentences, the pictures were displayed such that only one interpretation of the PP was possible. For target sentences, participants were free to choose from two pictures such that both interpretations of the PP were possible. The participants were more likely to select the syntactic interpretation that they had selected for the previous prime sentence (abstract priming) which was significantly enlarged when the same verb was repeated between prime and target trials (lexical boost).

Both abstract priming and lexical boost persisted over 1- and 2-intervening fillers, suggesting enduring facilitation over intervening time and intervening linguistic material.

While it is unequivocal that abstract (lexically-independent) and lexically-specific priming are operative in normal language processing, the cognitive bases underlying these priming effects are still being explored. Pickering and Branigan's (1998) residual activation account suggests that both types of priming are a transient boost from the remaining activation of recently processed linguistic representations. This boost is greater for the same verb primes due to additional activation from a shared head lemma. The adaptation account (Jaeger & Snider, 2013) proposes that both lexical boost and abstract priming arise from language users' tendency to implicitly adapt their expectations to the statistical distribution of information to ease information transfer in communication (see also Pickering & Garrod, 2004). The lexical boost effect occurs because lexical content tends to be over-distributed for a given conversation topic than structural content, allowing a prime with lexical overlap more statistical predictability for future expectation compared to a prime sentence without lexical overlap[1]. Because these models assume a single cognitive basis for abstract priming and lexical boost, no dissociation between the two is expected, at least when a target immediately follows a prime.

Others propose that long-term abstract priming reflects some sort of learning, whereas lexical boost reflects temporary (spreading) activation-based retrieval in short-term memory. Chang and colleagues (2006; 2012; Bock & Griffin, 2000) suggested that abstract priming is a consequence of prediction error-based implicit learning in the sequencing system. As an individual incrementally comprehends a prime sentence, the model predicts upcoming word order. When a different word order is encountered, this error is used to create small but lasting adjustments of connection weights in syntactic representations, thereby biasing the model's probability to use the primed structure in the future.

[1] The adaptation account (Jaeger & Snider, 2013) also accounts for fast decay of lexical boost. Interlocutors are aware that the dense informativity of lexical material would disappear once a new topic is discussed. Thus, the ephemeral lexical boost effect is caused by comprehenders' sensitivity to this fast decaying nature of lexical distribution in their linguistic environment.

However, the lexical boost effect reflects short-term retrieval of a lexically specific link to the structure in explicit memory. The repeated lexical item (verb, in this case) serves as a retrieval cue for short-term use of the linked structure, yielding a temporary boost in priming. Reitter et al. (2011) proposed that long-term abstract priming reflects an unsupervised learning mechanism that changes the base level activation for a structure with each instance of use or retrieval in declarative memory rather than prediction-error based learning. During priming, repeated retrieval of syntactic representations in memory changes the base-level activation for the primed structure, although there is some decay in activation as a power-law. This increase in base-level activation causes lasting priming effects. However, temporary lexical boost effects are purely due to spreading activation from the lexical-semantic cue to its related syntax, facilitating subsequent use only ephemerally. Under these models of structural priming, observing abstract priming in the absence of lexical boost would not be surprising, because they are subserved by two distinctive cognitive processes.

Growing evidence demonstrates that structural priming facilitates immediate and longer-term syntactic production in aphasia. PWA show increased production of target structures immediately following primes (Hartsuiker & Kolk, 1998; Saffran & Martin, 1997; Rossi, 2015; Verreyt et al., 2013). Priming effects also persist up to four intervening fillers (Cho-Reyes et al., 2016; Man, Branigan, & Lee, 2018) and up to a month following multiple sessions of priming training (Lee and Man, 2017), demonstrating structural priming may hold potential to create lasting improvement in PWA. Only two studies have examined the effect of same vs. different verb primes on sentence production in PWA, yielding inconsistent findings (Man et al., 2018; Yan, Martin, & Slevc, 2018). Yan et al. (2018) reported that both abstract priming and lexical boost effects remain intact in PWA and healthy older adults (HOA) by using a monologue production-to-production task where the participants heard and repeated active or passive primes immediately before description of transitive target pictures. In Man et al. (2018), however, PWA showed only abstract priming but not lexical boost using a dialogue-like comprehension-to-production priming task, indicating that abstract priming may be a more robust mechanism when primes are processed via a comprehension-only modality (see also Lee, Man, Ferreira, & Gruberg, under review). To our knowledge, no study has yet examined whether these mechanisms of structural priming effectively facilitate off-line and online sentence comprehension in aphasia and whether they create persistent effects.

The purpose of this study was to examine the effects of verb overlap on immediate and longer-term priming during comprehension of syntactically ambiguous sentences in PWA (e.g., *the chef is poking the waitress with an umbrella*). A written sentence-to-picture matching task was used (Pickering et al., 2013). Experiment 1 examined these priming effects when a target sentence immediately followed a prime sentence (0-lag), whereas Experiment 2 included two unrelated filler trials between each prime and target (2-lag), thereby examining the persistence of the structural priming effects over both time and (potentially interfering) linguistic material. The same participants were tested in both experiments with the order of the experiments counterbalanced. Participants' off-line picture identification choices and response times were measured in different prime conditions. We asked, first, if structural priming is preserved in the comprehension modality in PWA and HOA, facilitating disambiguation of the target sentences. Second, we asked if HOA and PWA demonstrate increased structural priming when the verb is repeated, indicating that the lexically (verb)-specific mechanism of priming is operative in their sentence comprehension. Last, we examined if the priming effects would persist over intervening fillers. We hypothesized that persistent priming effects over the lag in Experiment 2 would indicate that structural priming in sentence comprehension reflects some sort of learning beyond a transient boost in linguistic activation.

Experiment 1

Participants. We tested 20 HOA (7 males, 13 females; age mean = 73.1 yrs, range 60-82; education mean = 16.9 yrs, range 12-22) and 19 PWA (15 males; 4 females; age mean = 63.1 yrs old, range 50 – 80; education mean = 14.6 yrs, range 12- 20; 15-196 month post-left CVA). All participants were native speakers of English, passed a hearing screening at 40 dB at 500, 1000, and 2000 Hz in at least one ear, and reported normal or corrected-to-normal vision. Two PWA were able to complete only one experiment due to time constraints (A01: Experiment 1, A09: Experiment 2), resulting in 18 PWA per experiment. All HOA demonstrated normal composite severity ratings (mean Composite Rating Score (SD) = 3.98/4.0 (.061); normal range: 4.0 – 3.5) on the Cognitive Linguistic Quick Test (CLQT; Helm-Estabrooks, 2001), indicating the absence of age-related cognitive-linguistic decline.

PWA presented with mild-to-moderate fluent or nonfluent aphasias on the Western Aphasia Battery-Revised (WAB-R AQ range 44.1 – 92.9; Kertesz, 2006) as shown in Table 1. All participants showed relatively intact object knowledge and lexical-semantic comprehension as measured by the Pyramids and Palm Trees Test (PPT, Howard & Patterson, 1992) and the Spoken Word-Picture Matching Test of the Psycholinguistic Assessment of Language Processing in Aphasia (PALPA, Kay, Lesser, Coltheart, 1992). PWA showed accuracies higher than 80% on the Verb Comprehension Test of the Northwestern Assessment of Verbs and Sentences (NAVS, Thompson, 2011), indicating sufficiently intact processing of verb information to complete the experimental task, although their verb naming scores were more varied (ranged from 40.9 – 100% on the Verb Naming Test). On the sentence comprehension tests of the NAVS, PWA generally performed worse on non-canonical (passives, object wh-questions, object relative clauses) structures than on canonical (actives, subject wh-questions, and subject relative clauses) structures. However, all but one PWA performed above chance on the canonical sentences, indicating functional comprehension at the sentence level at least for simpler sentences. In addition, all PWA showed greater than 80% accuracy on the written word comprehension test of the BDAE, except for A12 (60% accuracy).

[Insert Table 1 here]

Stimuli. Both linguistic and visual stimuli were adapted from Pickering et al. (2013). Six unique verbs (*hit, poke, prod, injure, hurt,* and *thump*) were used to create the prime and target sentences. Each verb was repeated 8 times with different sets of nouns, resulting in a total of 48 sentences with a prepositional phrase (e.g., *the clown is hitting the ballerina with the umbrella*). The first 24 sentences were directly taken from Pickering et al. (2013). An additional 24 sentence stimuli and corresponding pictures were created by rearranging existing nouns from the original 24 sentences and modifying the original pictures. The same sentence was used once as a prime and once as a target. An additional 96 fillers were prepared, including 29 intransitive, 48 transitive, and 19 dative action pictures and corresponding written sentences (e.g., *the boy is running*; *the girl is wrapping a gift*; *the waiter is giving a menu to the lady*). Each filler item was repeated once, resulting in a total of 192 fillers. Two fillers preceded a prime and two fillers followed a target, but they did not appear in between the prime and the target. Thus, each prime-target pair was associated with four filler items.

Two lists were created for Experiment 1. Each list was comprised of 48 prime and target pairs and 192 filler items. Within each list, the verb was repeated between the prime and the target for half of the prime-target pairs (same verb: *the cop is prodding the doctor with a gun* - *the teacher is prodding the ballerina with an umbrella*). Different verbs were used for the other 24 prime-target pairs (*the swimmer is thumping the clown with a book* - *the doctor is hitting the teacher with a sword*). The order of the same vs. different verb pairs was counterbalanced across the lists (same verb for items 1-24 for list 1 and different verb for items 25-48 for list 2). In addition, within the same or different verb prime-target pairs, the first 12 primes were designated as a high attachment (HA) interpretation, whereas the prime was disambiguated as a low attachment (LA) interpretation for the other 12 pairs. Trials within a list were pseudo-randomized such that no more than three same-verb or three different-verb trials were presented consecutively.

Procedure. A written sentence-picture matching task was used (Figure 1). For a prime sentence, one picture was disambiguated for either a HA or LA interpretation and one picture matched neither interpretation. With this set-up, a particular (HA or LA) interpretation could be forced for the prime sentence. Then, the participants read a target sentence which was paired with two pictures, one matching the HA and the other matching the LA interpretation. The participant was free to choose either picture.

We coded the participant's syntactic interpretation as 'primed' if the participant selected a target picture that had the same interpretation as the prime (HA as exemplified in Figure 1) as opposed to the target picture that had the alternative interpretation (LA).

Stimuli were presented on a 20-inch monitor using Experiment Builder (SR Research). Participants were instructed to silently read the written sentence as fast and as accurately as they could, which was presented for up to 7 seconds for HOA and 12 seconds for PWA. They were asked to press any key on the keyboard to advance to the next slide once they understood the sentence. Upon pressing a key, or after 7 seconds (for HOA) and 12 seconds (for PWA), the sentence disappeared, and the two pictures were presented on the screen. Participants decided which picture matched the previous sentence by pressing a matching key on the keyboard. No time limit was imposed for picture identification. Participants' response choices as well as response times were recorded for both prime and target items.

Prior to the experimental task, participants were 'familiarized' with the single verbs and nouns that were included in the sentence stimuli using a stimuli book. The participant read aloud single nouns (e.g., 'chef'), presented with the image of their corresponding characters, and written single verbs (e.g., 'hit'). When PWA failed to correctly read the words, feedback was provided. The familiarization task was done to minimize any influence from aphasic participants' difficulties with word comprehension in the experimental task. Following familiarization, participants completed 8 practice trials before the start of the experiment. Participants were offered a rest break every 72 items to avoid fatigue. Each participant received both list 1 and 2 in two separate sessions with at least two weeks between sessions. The order of list presentation was counterbalanced across the participants.

Data analysis. Each participant completed 96 target items in total, 24 in each condition: same verb-HA, same verb-LA, different verb-HA, and different verb-LA prime conditions. We first removed prime trials where participants incorrectly identified a picture. Then, we removed trials with an extreme response time on either the prime or target (less than 500 milliseconds or greater than 3 SD's from the participant's mean), to minimize extraneous influences[2]. A 2 (group) x 2 (prime type) mixed ANOVA was conducted to compare group differences in accuracy of the task.

Further statistical analyses included only the correct trials. To examine priming effects on off-line responses, mixed-effects logistic regressions were used (*lme 4* package in R, Bates, Maechler, Bolker, & Walker, 2014). Participants' target picture choices were binarized according to whether they chose the HA (1) or LA picture (0). Given that only two alternating choices were possible for target responses, it was tested if probability of a specific response (HA target response, in our case) would increase as an effect of different prime conditions. For analysis of response times, participants' response times were first square-root transformed and entered into linear mixed-effects regressions (Baayen, 2008). It was tested if participants showed faster response times for primed (when choosing the same interpretation as the prime, i.e., HA prime-HA target; LA prime-LA target response) vs. unprimed (when choosing the different interpretation as the prime, i.e., HA prime-LA target; LA prime-LA target) responses.

For both logit and linear regressions, data were first modeled separately for each participant group, entering prime, verb, experiment order, and their interactions as predictors. Secondly, to test group differences, a separate model was used including prime, verb, group, and their interactions as predictors. Experimental order was included as a factor in within-group models to test if the order in which the participants received Experiment 1 and 2 modulated priming or lexical boost effects (i.e., practice effects) in the participants. The factor of experimental order was excluded from the between-group models, because within-group models confirmed that experiment order did not influence priming or lexical boost effects in either group (i.e., no significant order x prime or order x prime x verb interactions). All models initially contained maximal random effect structures. If the model did not converge, the by-item slopes for fixed factors were removed to achieve model convergence. To determine whether each predictor

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[2] In Experiment 1, an additional 2.1% of the data were removed for each group due to extreme response times. In Experiment 2, an additional 2.4% and 2.3% of the data were removed for HOA and PWA, respectively.

significantly improved the model fit, ANOVA model comparison was run with α = .05, using a log-likelihood ratio test.

Results and summary

Accuracy on primes: The group mean accuracies are provided in Table 2. PWA showed lower accuracy than HOA in general (81% vs. 97%), $F(1, 36) = 66.86$, $p < .001$. However, all PWA performed above chance level on the task, as indicated by accuracies ranging from 66 – 93%. In general, both groups showed higher accuracy for HA primes than LA primes, $F(1, 36) = 10.24$, $p < .01$, and the group difference was greater for the LA primes than for the HA primes, $F(1, 36) = 4.95$, $p < .05$.

[insert Table 2 here]

Priming effects on off-line target responses: Table 3 and Figure 2 show off-line sentence comprehension data. Table 4 shows the results of logit models for Experiment 1. We report a log-odds estimate, standard error, and a chi-square statistic from a log-likelihood ratio test (ANOVA) and its associated *p*-value for each predictor. A significant *p*-value indicates that the given fixed factor significantly improved model fit after ANOVA model comparison.

For HOA, prime type significantly improved the model fit, indicating that HOA were more likely to make a HA target response following HA primes compared to LA primes in general. The effect of the verb was not significant, indicating that the overall frequency of HA responses was not different between verb types. Importantly, the prime x verb interaction was not significant: HOA did not show increased priming when the verb was repeated compared to when different verbs were used between prime and target, i.e., no lexical boost. Additionally, the order that participants completed the experiments (either Experiment 1 first or Experiment 2 first) did not improve model fit or did not interact with other predictors.

For PWA, the prime effect was significant, indicating that they were more likely to choose HA responses following HA vs. LA primes (mean 10% difference). Importantly, neither the effect of the verb nor the prime x verb interaction improved model fit, indicating no lexical boost effect. The significant effect of experiment order indicates that PWA who completed Experiment 2 first chose HA responses more frequently than those who completed Experiment 1 first. However, experiment order did not show any significant 2- or 3-way interaction involving a prime effect. The mixed-effects model comparing the two groups further confirmed that only the effect of prime type was significant. No other main or interaction effect was significant.

[insert table 3 & 4 here]

[insert Figure 2 here]

Priming effects on response times: Figure 3 and Table 5 summarize response time data and Table 6 summarizes statistical results. Within-group models revealed a significant effect of prime for both HOA and PWA, such that they showed significantly shorter response times on target items when they chose the interpretation consistent with the prime (HA response after HA prime; LA response after LA prime) compared to when they chose the interpretation inconsistent with the prime (HA response after LA prime or vice versa). However, no other effects were significant, including prime x verb interaction, thus there was no lexical boost. The model for group comparisons revealed significantly longer response times for PWA than HOA (group effect) as well as the effect of prime. No other effect improved the model fit.

[insert Table 5 & 6 here]

[insert Figure 3 here]

In summary, both HOA and PWA showed significant abstract priming but not a lexical boost effect at 0-lag. In addition, the magnitudes of priming effects did not differ between the two groups. Parallel to the off-line data, only abstract priming effects were found in response time data. Both PWA and HOA were faster when they disambiguated the target sentences in the same way as the prime.

Experiment 2

Methods

Participants. The same participants (20 HOA, 18 PWA excluding A01) from Experiment 1 were tested in Experiment 2. As mentioned earlier, the order of the experiments was counterbalanced across the participants with at least 2 weeks apart between experiments.

Stimuli, procedure, and data analysis. The same experimental and filler items from Experiment 1 were used in Experiment 2. The stimuli were rearranged such that two fillers interceded between a prime and a target, creating a 2-lag condition. All the experimental procedures and data analyses remained the same.

Results and summary

Accuracy on primes: PWA showed lower accuracy in general than HOA (84% vs. 92%), $F(1, 36) = 10.46$, $p < .01$. All PWA performed higher than chance-level performance on prime items (66-95% correct). Both groups showed higher accuracy for HA primes than LA primes, $F(1, 36) = 24.3$, $p < .001$. However, there was no prime type x group interaction, $F(1, 36) = .013$, $p > .90$.

Priming effects on off-line responses: Table 7 summarizes statistical results for Experiment 2. HOA showed a significant priming effect, indicated by a higher proportion of HA target responses (10% difference) following HA primes compared to LA primes. No other effects significantly improved the model fit. For the results from PWA, the priming effect remained significant. They were 12% more likely to choose an HA interpretation on target sentences following HA primes, compared to LA primes. No verb or verb x prime interaction improved model fit. Experiment order interacted with verb type in PWA, indicating that those who received Experiment 2 first made HA responses more frequently in the same-verb condition than those who received Experiment 2 after completing Experiment 1. However, this interaction does not have a theoretical bearing other than showing there was no practice effect on the result. Experiment order did not interact with the other predictors. The model for group comparisons revealed that only the effect of prime type was significant, confirming the results from the within-group models. .

[insert Table 7 here]

Priming effects on response times: For HOA, none of the main or interaction effects was significant (Table 8). HOA showed only numerically shorter response times for primed vs. unprimed target responses (Figure 3). For PWA, the effect of prime was not significant, but there was a significant prime x verb interaction. However, this interaction might have been driven by 'reversed' priming in the different verb condition (increased response times for primed responses); thus, it is difficult to tell whether this interaction truly indicates a significant lexical boost. The remaining predictors were not significant in PWA. The overall model revealed a group effect, indicating generally longer response times in PWA than in HOA. The prime x verb interaction and the 3-way prime x verb x group interaction were also significant, likely driven by the prime x verb interaction in PWA.

[insert Table 8 here]

To summarize, HOA and PWA continued to show only abstract priming over the lag of 2 intervening fillers in off-line target responses, with the magnitude of priming being similar between the groups. However, no clear evidence of a priming effect was shown on participants' response times, different from the results of Experiment 1.

General Discussion

The current study examined immediate and longer-term effects of lexically-independent (abstract structural) and lexically-specific (lexical boost) priming during comprehension of syntactically ambiguous sentences in HOA and PWA. In off-line target interpretation, both HOA and PWA tended to disambiguate the target sentence in the same way as the prime sentence at both immediate (0-lag) and longer-term (2-lag) intervals. Notably, the magnitude of abstract priming effects in our HOA (overall 12% at 0-lag; 10% at 2-lag) is not smaller than those found in the young adults (6% at 0-lag, 8% at 2-lag following different verb primes) of Pickering et al. (2013). Further, PWA showed similar magnitudes of priming as HOA (10% at 0-lag and 12% at 2-lag), as evidenced by the absence of prime by group interactions in both experiments. However, neither group showed enhanced priming when the verb was repeated between prime and target, in contrast to significant lexical boost found in the young adults of Pickering et al. (2013).

Complementing the off-line comprehension data, the analysis of participants' response times showed some evidence that abstract priming is preserved during on-line sentence comprehension. When the target and prime items were presented consecutively (Experiment 1), both HOA and PWA showed shorter response times when choosing the same target interpretation as the prime compared to when choosing the different interpretation from the prime. The priming effect was not enhanced by verb overlap. When there were intervening utterances (Experiment 2), HOA showed a numeric trend towards shorter response times for primed responses, and PWA showed shorter response times for primed responses only in the same verb condition. However, because our experimental task did not place time constraints on participants' speed of response, we interpret the findings with caution; future investigation requires more sensitive on-line measures.

The current findings are the first demonstration that structural priming facilitates sentence comprehension in aphasia, specifically syntactic ambiguity resolution, extending the burgeoning evidence of reliable structural priming effects found in previous sentence production studies in aphasia (Hartsuiker & Kolk, 1998; Saffran & Martin, 1999; Yan et al., 2018; Cho-Reyes et al., 2016; Man et al., 2018). The evidence of preserved abstract structural priming in both modalities suggests that common syntactic representations are involved and accessed via priming in both comprehension and production (Branigan & Pickering, 2017; Pickering & Garrod, 2004; see also Berndt & Caramazza, 1980; Caramazza & Zurif, 1979 for evidence of amodal syntactic representations in aphasia). However, our study cannot speak to whether and to what extent the same processing mechanisms are operative between modalities without more systematic evidence from cross-modal (comprehension-to-production, production-to-comprehension) priming. For example, some studies of syntactic treatment report lack of cross-modal generalization in PWA (Adelt, Hanne, & Stadie, 2016; Schroder, Burchert, & Stadie, 2015), indicating that there can be modality-specific cognitive processes associated with effective priming in comprehension vs. production. Nonetheless, the theories suggesting loss of syntactic representations in aphasia (e.g., Friedmann & Grodzinsky, 1997) have difficulty in explaining the intact structural priming effects seen in our PWA. Instead we argue that structural priming may overcome computational overload during syntactic parsing, facilitating activation and selection of syntactic structures in comprehension. Specifically, the preserved abstract priming found in the current study suggests that PWA retain abilities to process constituent assembly at the 'positional' level (Levelt & Bock, 1994) and this process could be strengthened via structural priming.

Interestingly, we failed to find evidence of preserved lexical boost. The absent lexical boost effect in HOA clearly deviates from robust lexical boost effects seen in young adults in prior studies (Branigan et al., 2005; Branigan & McLean, 2016; Hartsuiker et al., 2008; Pickering et al., 2013; Tooley & Bock, 2014) and the lexical boost seen in older adults using a dialogue-based production priming task (Hardy et al., 2017). Since we used essentially the same stimuli and task as Pickering et al. (2013), the null results regarding verb overlap are most likely due to cognitive changes in aging. One possibility is that our HOA might not have encoded lexical-semantic information of the verb in depth to compensate for their cognitive limitations (Christianson et al., 2008; Swets et al., 2008). Our experimental task did not obligate using the lexical-semantic information of the verb in order to accurately identify a matching picture for prime sentences. HOA might have relied primarily on the syntactic attachment of the prepositional phrase of the prime (whether it is attached to the verb or the object noun) to draw a plausible meaning for the sentence and find a matching picture rather than exhaustively encoding both structural and verb information. This 'less-than-complete' processing might have yielded a reduced effect of lexical-semantic content on priming, while serving age-related cognitive reductions.

The lack of lexical boost in our PWA is consistent with Man et al. (2018), where their PWA failed to show increased verb-specific boost on syntactic production when they simply heard their partner's sentences (primes) in a dialogue-like task. Our finding is at odds with Yan et al. (2018), who found a normal lexical boost in PWA (mean 12% increase, similar to control participants). However, Yan et al.'s priming task obligated participants to repeat the prime sentence and then compare their own repetition with the written prime sentence. This feature might have caused PWA to encode and reuse the verb in their own subsequent sentence production more effectively (Branigan, Pickering, McLean, and Cleland, 2007). When primes are processed in comprehension only, impaired lexical (verb semantic, in this case) processing in aphasia may diminish the lexical boost effect in PWA. As proposed by other researchers, abnormally slowed activation of lexical items in PWA may feed syntactic processing too slowly to influence their disambiguation of prepositional phrase attachment (Ferrell et al., 2012; Love et al., 2008; Prather et al., 1993). Alternatively, PWA may experience difficulty integrating activated lexical items with other (syntactic) representations during sentence comprehension (Swaab et al., 1998; Thompson & Choy, 2010; Mack et al., 2013). The current results still demonstrate a clear dissociation between lexically-independent and lexically-specific priming mechanisms in PWA. They, in turn, support the models of structural priming that assume two distinctive cognitive bases underlying lexically-independent and lexically-specific priming (Chang et al., 2012; Reitter et al., 2011), and further suggest that these two mechanisms of priming can be selectively affected in individuals with aphasia.

The findings of particular importance in this study is that our HOA and PWA showed persistent abstract priming over intervening utterances in Experiment 2, suggesting that the structural priming effects are not simply due to a transient activation of previously encountered linguistic representations. Rather, these findings are consistent with the models of structural priming that posit that structural priming reflects life-long implicit learning of syntax (Chang et al., 2006; 2012; Reitter et al., 2011; Bock & Griffin, 2000). Moreover, they indicate that this learning-based mechanism of structural priming remains preserved and operative into aging and in impaired systems, as has been shown in previous production-based priming studies with aphasia (Cho-Reyes et al., 2016; Man et al., 2018). According to Chang et al. (2006; 2012), implicit abstract priming is a consequence of prediction-error-driven weight changes in syntactic representations. Thus, one's ability to predict upcoming structures in sentence comprehension would be essential to yield priming effects. Within this framework, the persistent abstract priming in our PWA would indicate that their predictive mechanisms during sentence comprehension are intact, in line with previous studies demonstrating intact predictive abilities during sentence comprehension in PWA (Hanne et al., 2015; Thompson & Choy, 2009; Warran et al., 2016). On the other hand, Reitter et al. (2004) attribute lasting priming effects to increased base-level activation following repeated retrievals of the primed structure in the declarative memory system, rather than implicit memory processes. In this view, persistent abstract priming in our PWA would indicate preserved declarative learning. We leave this question to future investigation.

The current findings inform clinical practice in aphasia. Consistently reported evidence of intact abstract priming at 0-lag in the literature so far suggests that structural priming can be used in assessment of aphasia to test the integrity of the relevant representations and the ability to access them in the PWA, with minimal reliance on metalinguistic processes as in a grammatical judgement task (see also Branigan & Pickering, 2017 for a similar view). Increasing the lag between the prime and target would not only test the person's ability to retain 'primed' message-structure mappings in their system but could also be incorporated into a treatment program. Indeed, some existing studies have already used variants of structural priming as part of their treatment protocol targeting comprehension and production of sentences (e.g., Thompson et al., 2003; Lee & Man, 2017; cf. Schuchard & Thompson, 2017). For example, in the Treatment of Underlying Form, a clinician uses a prime sentence to explicitly train the client to construct a similar sentence structure. Lee and Man (2017) reported a case of an individual with agrammatic aphasia, who received an implicit structural priming training that was disguised as an oral reading task and included a lag of 4 intervening fillers between prime and target. The participant showed significant improvement in production of untrained sentences and connected speech.

The methodological limitations of the present study includes the lack of comprehensive assessment of reading comprehension abilities in PWA. Thus, we cannot rule out the possibility that some of the current results might have been affected by individuals' deficits in reading comprehension, since the participants were required to read the prime and target sentences. The findings also need to be replicated with a larger number of verbs of varied semantic categories, given that we included only a limited number and one semantic category of verbs. Lastly, investigating temporal indices of lexically-independent and -specific priming using more sensitive on-line tools will lead to clearer understanding of the mechanisms and time course of structural priming in aphasia.

In conclusion, the current study examined the mechanisms of structural priming during sentence comprehension in aphasia. Similar to previous production priming studies in aphasia, our PWA demonstrated preserved abstract priming at both immediate and delayed priming conditions. In addition, their magnitude of priming effects was as large as that seen in HOA. However, there was no evidence of reliable lexical boost effects in both groups of participants, different from robust lexically-specific priming during sentence comprehension in young adults. These novel findings suggest that structural priming remains preserved in the domain of sentence comprehension, effectively guiding subsequent preferences of structure-message encoding. The findings also demonstrate that abstract structural priming reflects implicit language learning and remains preserved in aphasia, and that the lexically-independent and -specific mechanisms of priming can be selectively affected in aphasia.

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Table 1. Language testing data for PWA

	WAB-R						NAVS (%)			
Participant	Fluency	AC	AQ	PPT (%)	PALPA	BDAE	VNT	VCT	SCT_C	SCT_NC
A01	4.0	8.4	74.3	82.7	92.5	80	79.0	81.8	60.0	60.0
A02	9.0	9.4	92.9	98.1	97.5	100	91.0	100.0	100.0	100.0
A03	5.0	10.0	83.0	100.0	97.5	100	97.0	100.0	100.0	100.0
A04	6.0	9.1	84.6	100.0	100	100	100.0	100.0	100.0	93.0
A05	5.0	8.7	69.6	98.1	100	90	72.7	100.0	93.3	26.7
A06	4.0	6.5	57.0	90.4	97.5	90	68.2	100.0	60.0	33.3
A07	2.0	9.8	44.1	98.1	97.5	100	81.8	100.0	93.3	26.7
A08	6.0	8.8	77.0	98.1	97.5	100	50.0	100.0	80.0	60.0
A09	4.0	8.3	66.8	80.8	97.5	100	54.5	100.0	53.3	26.7
A10	9.0	9.9	93.1	100.0	97.5	100	95.5	100.0	100.0	100.0
A11	8.0	5.3	70.3	90.4	90	90	80.0	100.0	60.0	33.3
A12	9.0	8.7	91.6	94.2	100	60	72.7	100.0	86.7	100.0
A13	4.0	8.5	75.7	98.1	95	90	86.4	100.0	86.7	93.3
A14	8.0	6.7	75.0	88.5	95	90	77.3	86.4	73.3	46.7
A15	4.0	8.9	66.9	86.5	100	100	40.9	100.0	80.0	66.7
A16	6.0	8.8	83.0	86.5	97.5	100	63.6	100.0	100.0	80.0
A17	6.0	8.9	82.9	94.2	97.5	80	86.4	100.0	46.7	60.0
A18	8.0	9.6	89.2	92.3	97.5	100	95.5	100.0	100.0	93.3
A19	6.0	9.0	78.6	84.6	92.5	100	95.5	100.0	93.3	100.0
MEAN	5.9	8.6	76.6	92.7	96.8	93.2	78.3	98.3	82.5	68.4
SD	2.1	1.2	12.6	6.3	2.7	10.6	16.9	5.1	17.7	28.4

Note: AC = Auditory Comprehension, AQ = Aphasia Quotient; PPT = Pyramid Palm Trees Test (percent correct); PALPA = Psycholinguistic Assessment of Language Processing in Aphasia Spoken Word Picture Matching Test (%); BDAE Word ID = Boston Diagnostic aphasia Examination Word Identification Subsection (%); VNT = Verb Naming Test (%); VCT = Verb Comprehension Test (%); SCT_C = Sentence Comprehension Test - Canonical; SCT_NC = Sentence Comprehension Test – Non-canonical structures

Table 2. Accuracy (%) of picture identification (with standard deviations) for prime sentences in Experiments 1 and 2.

	HA primes	LA primes	Overall
Experiment 1 (0-lag)			
HOA	0.97 (0.02)	0.96 (0.03)	0.97 (0.02)
PWA	0.84 (0.11)	0.78 (0.09)	0.81 (0.09)
Experiment 2 (2-lag)			
HOA	0.96 (0.04)	0.88 (0.11)	0.92 (0.06)
PWA	0.87 (0.09)	0.80 (0.10)	0.84 (0.09)

Table 3. Proportions of HA and LA target responses in each prime condition (HA = high attached; LA = low attached).

Experiment	Group	Target response	Same verb		Different verb	
			HA prime	LA prime	HA prime	LA prime
1. 0-lag	HOA	HA target	0.56	0.42	0.56	0.47
		LA target	0.44	0.58	0.44	0.53
	PWA	HA target	0.59	0.45	0.53	0.43
		LA target	0.41	0.55	0.47	0.57
2. 2-lag	HOA	HA target	0.61	0.50	0.60	0.50
		LA target	0.39	0.50	0.40	0.50
	PWA	HA target	0.61	0.47	0.57	0.46
		LA target	0.39	0.53	0.43	0.54

Table 4. Summary of the mixed-effects logistic regression models for Experiment 1, priming effects on off-line target responses

Predictors	Estimate	Std. error	χ^2	*p*-Value
Priming effects: HOA				
(Intercept)	-0.091	0.280		
Prime (HA vs. LA)	0.299	0.281	4.930	< .05
Verb (same vs. different)	-0.521	0.330	1.251	0.263
Expt Order	0.269	0.434	0.406	0.523
Prime x Verb	0.442	0.432	0.602	0.437
Prime x Expt Order	0.007	0.300	0.333	0.563
Verb x Expt Order	0.271	0.308	0.305	0.580
Prime x Verb x Expt Order	-0.290	0.417	0.486	0.485
Priming effects: PWA				
(Intercept)	-0.062	0.282		
Prime (HA vs. LA)	0.444	0.243	7.727	< .01
Verb (same vs. different)	0.008	0.308	1.96	0.161
Expt Order	-0.694	0.484	4.870	< .05
Prime x Verb	0.207	0.358	0.099	0.751
Prime x Expt Order	-0.019	0.399	0.230	0.631
Verb x Expt Order	0.421	0.403	0.838	0.359
Prime x Verb x Expt Order	-0.271	0.500	0.294	0.587
Priming effects: HOA and PWA				
(Intercept)	-0.337	0.245		
Prime (HA vs. LA)	0.515	0.208	10.714	< .001
Verb (same vs. different)	0.175	0.239	0.270	0.603
Group (HOA vs. PWA)	0.400	0.361	0.010	0.919
Prime x Verb	0.020	0.311	0.738	0.390
Prime x Group	-0.387	0.288	0.691	0.405
Verb x Group	-0.557	0.315	1.958	0.161
Prime x Verb x Group	0.432	0.400	1.170	0.279

Reference levels are as follows: Prime, LA; Verb, different; Group, HOA; Expt Order, Expt 1 first. Superscripts indicate random slopes that were included in the final model; P, participant; I, Item. Random intercepts were included on both participants and items in all models.

Table 5. Mean response times (in milliseconds) for each type of target response as an effect of prime condition (HA = high attached; LA = low attached).

Experiment	Group	Target response	Same verb		Different verb	
			HA prime	LA prime	HA prime	LA prime
1. 0-lag	HOA	HA target	4,054	4,221	4,189	4,193
		LA target	4,460	4,296	4,518	4,192
	PWA	HA target	5,907	6,101	6,363	6,660
		LA target	6,598	6,370	6,837	6,406
2. 2-lag	HOA	HA target	4,343	4,397	4,439	4,400
		LA target	4,107	4,022	4,599	4,304
	PWA	HA target	6,935	7,236	7,597	7,180
		LA target	7,646	6,758	7,289	7,571

Table 6. Summary of mixed-effects linear regression models for Experiment 1, priming effects on target response times.

Predictors	Estimate	Std. error	χ^2	*p*-Value
Priming effects: HOA ^{P,I}				
(Intercept)	62.97	2.587		
Prime (primed vs. unprimed)	-0.852	2.430	5.07	< .05
Verb (same vs. different)	-0.155	0.386	0.149	0.699
Expt Order	-3.655	1.419	2.014	0.155
Prime x Verb	0.219	-0.641	0.410	0.521
Prime x Expt Order	-0.544	1.856	3.443	0.064
Verb x Expt Order	-0.380	1.206	1.453	0.227
Prime x Verb x Expt Order	0.312	-1.106	1.222	0.268
Priming effects: PWA ^{P,I}				
(Intercept)	75.83	4.109		
Prime (primed vs. unprimed)	-1.144	0.523	4.780	< .05
Verb (same vs. different)	-0.551	0535	1.062	0.302
Expt Order	-2.960	4.107	0.519	0.471
Prime x Verb	0.698	0.465	2.245	0.134
Prime x Expt Order	-0.282	0.520	0.293	0.587
Verb x Expt Order	-0.182	0.514	0.125	0.723
Prime x Verb x Expt Order	-0.689	0.462	2.224	0.135
Priming effects: HOA and PWA ^{P}				
(Intercept)	69.71	2.171		
Prime (primed vs. unprimed)	-1.041	0.283	13.54	< .001
Verb (same vs. different)	-0.399	0.345	1.334	0.247
Group (HOA vs. PWA)	6.781	2.161	9.840	<.01
Prime x Verb	0.341	0.257	1.760	0.184
Prime x Group	0.168	0.282	0.355	0.550
Verb x Group	0.181	0.279	0.421	0.516
Prime x Verb x Group	-0.222	0.256	0.753	0.385

Note: Reference levels are as follows: Prime, unprimed target responses; Verb, different; Group, HOA; Expt Order, Expt 1 first. Superscripts indicate random slopes that were included in the final model; P, participant; I, Item. Random intercepts were included on both participants and items in all models.

Table 7. Summary of mixed-effects logistic regression models for Experiment 2, priming effects on off-line target responses

Predictors	Estimate	Std. error	χ^2	*p*-Value
Priming effects: HOA^{P,I}				
(Intercept)	0.090	0.267		
Prime (HA vs. LA)	0.206	0.243	10.934	< .001
Verb (same vs. different)	-0.276	0.278	0.002	0.884
Expt Order	-0.031	0.506	0.505	0.423
Prime x Verb	0.269	0.352	0.590	0.437
Prime x Expt Order	0.449	0.309	3.115	0.078
Verb x Expt Order	0.325	0.321	1.490	0.222
Prime x Verb x Expt Order	-0.094	0.437	0.047	0.828
Priming effects: PWA^{P,I}				
(Intercept)	0.031	0.201		
Prime (HA vs. LA)	0.429	0.213	20.650	< .001
Verb (same vs. different)	-0.300	0.215	0.909	0.340
Expt Order	-0.358	0.291	0.394	0.528
Prime x Verb	0.311	0.298	1.132	0.287
Prime x Expt Order	-0.041	0.316	0.287	0.592
Verb x Expt Order	0.632	0.319	5.799	<.05
Prime x Verb x Expt Order	-0.168	0.440	0.147	0.701
Priming effects: HOA and PWA^{P,I}				
(Intercept)	-0.110	0.147		
Prime (HA vs. LA)	0.401	0.169	24.38	< .001
Verb (same vs. different)	-0.077	0.189	0.589	0.442
Group (HOA vs. PWA)	0.218	0.296	0.494	0.481
Prime x Verb	0.293	0.246	1.660	0.197
Prime x Group	-0.016	0.230	0.087	0.767
Verb x Group	-0.045	0.243	0.214	0.643
Prime x Verb x Group	-0.068	0.327	0.043	0.835

Reference levels are as follows: Prime, LA; Verb, different; Group, HOA; Expt Order, Expt 1 first. Superscripts indicate random slopes that were included in the final model; P, participant; I, Item. Random intercepts were included on both participants and items in all models.

Table 8. Summary of mixed-effects linear regression models for Experiment 2, priming effects on target response times.

Predictors	Estimate	Std. error	χ^2	*p*-Value
Priming effects: HOA^{P,I}				
(Intercept)	63.31	2.851		
Prime (primed vs. unprimed)	-0.499	0.344	2.096	0.147
Verb (same vs. different)	-0.243	0.381	0.405	0.524
Expt Order	1.909	2.847	0.449	0.502
Prime x Verb	-0.033	0.306	0.012	0.912
Prime x Expt Order	0.083	0.337	0.060	0.805
Verb x Expt Order	0.476	0.351	1.836	0.175
Prime x Verb x Expt Order	-0.154	0.298	0.268	0.604
Priming effects: PWA^{P,I}				
(Intercept)	81.17	4.449		
Prime (prime vs. unprimed)	-0.218	0.634	0.118	0.730
Verb (same vs. different)	-0.818	0.600	1.856	0.172
Expt Order	-0.863	4.450	0.037	0.846
Prime x Verb	1.171	0.504	5.397	<.05
Prime x Expt Order	-0.505	0.608	0.690	0.405
Verb x Expt Order	0.799	0.613	1.698	0.192
Prime x Verb x Expt Order	-0.115	0.471	0.060	0.806
Priming effects: HOA and PWA^{P}				
(Intercept)	72.27	2.595		
Prime (prime vs. unprimed)	-0.395	0.337	1.372	0.241
Verb (same vs. different)	-0.470	0.363	1.679	0.195
Group (HOA vs. PWA)	8.976	2.591	11.97	<.01
Prime x Verb	0.567	0.269	4.419	<.05
Prime x Group	0.109	0.337	0.105	0.745
Verb x Group	0.254	0.328	0.599	0.438
Prime x Verb x Group	-0.611	0.269	5.165	<.05

Note: Reference levels are as follows: Prime, unprimed target responses; Verb, different; Group, HOA; Expt Order, Expt 1 first. Superscripts indicate random slopes that were included in the final model; P, participant; I, Item. Both by-participant and by-item random intercepts were included in all models.

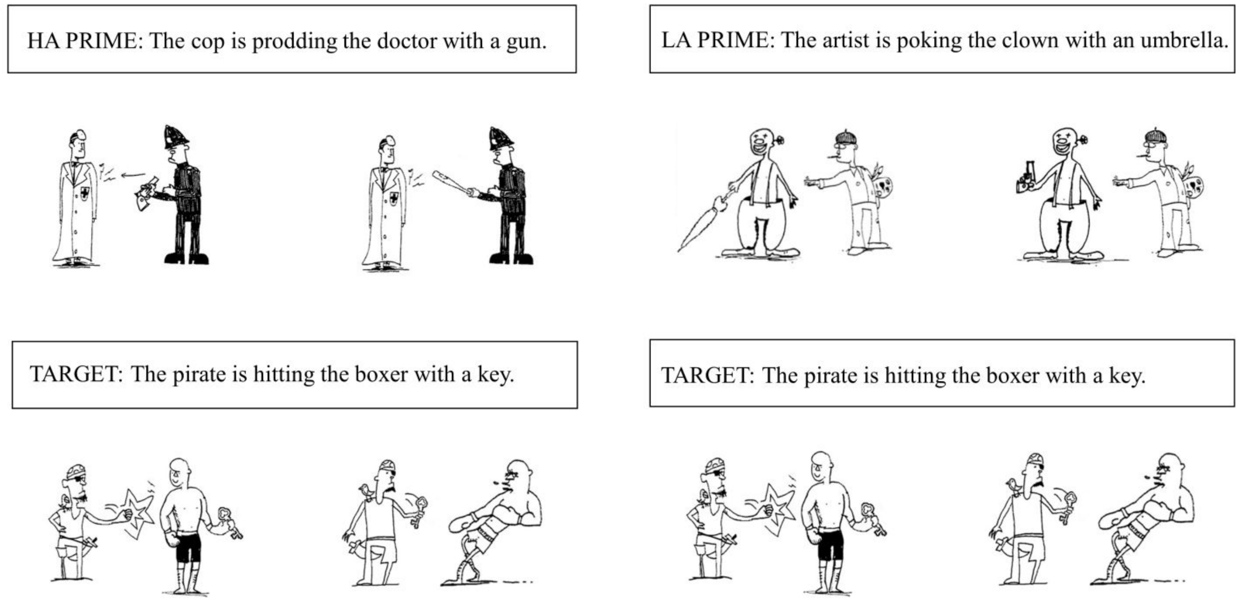

Figure 1. An example set of prime-target trials for the different verb prime condition. The prime sentence is disambiguated for a high attachment (HA) interpretation on the left side and for a low attachment (LA) interpretation on the right side. For the target sentence, alternating interpretations are allowed.

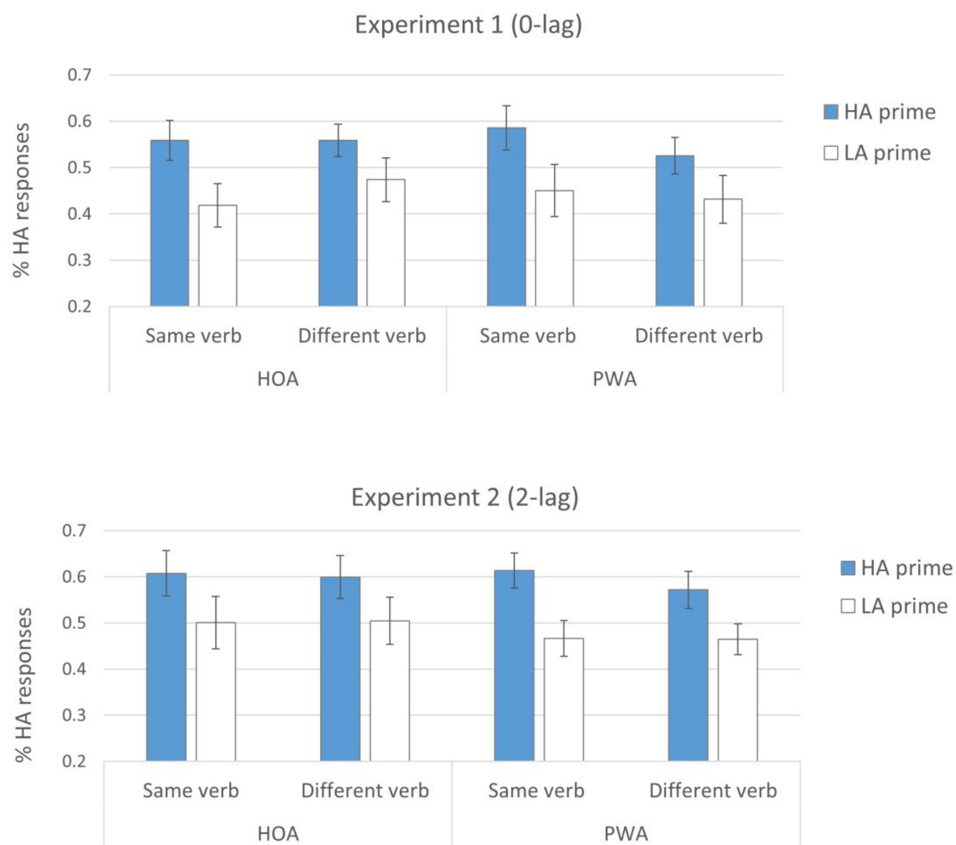

Figure 2. Proportions of HA target responses (out of all HA and LA target responses) in different prime conditions (with standard errors).

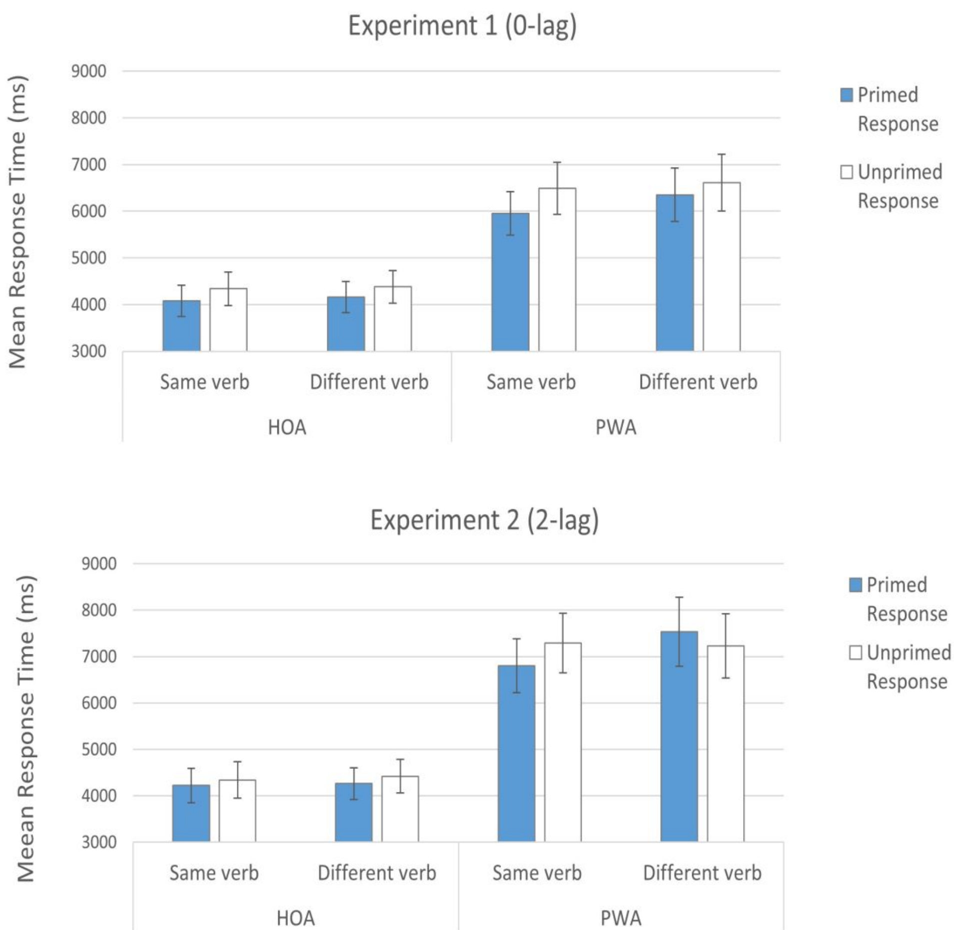

Figure 3. Comparisons of mean response times in milliseconds for primed vs. unprimed target responses. Error bars indicate standard errors.